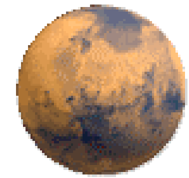

Technologies for Exploring the Martian Subsurface

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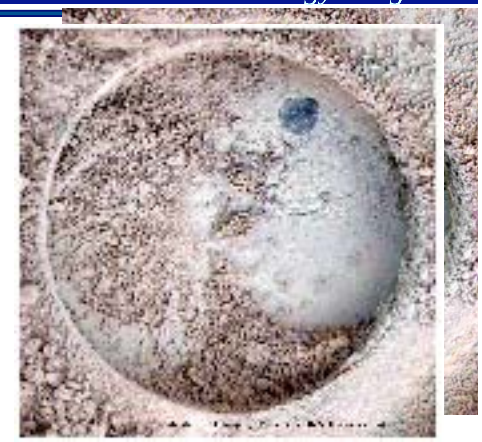
Accessing the Martian Subsurface



- **Demonstrated capabilities**
  - Depth record (hard rock) - MER (Mars Exploration Rover) RAT (Rock Abrasion Tool), 8.12 mm
  - Depth record (regolith) - Viking arm trenching, ~20 cm
- **On Deck**
  - Phoenix Lander: 2007 launch to the northern latitudes of Mars to dig in regolith (up to 1 m) to access and sample the permafrost surface (~1cm depth)
  - Mars Science Laboratory: 2009 launch to the mid-latitudes and collect core samples of hard rock and regolith to depths of 10 cm below the surface
- **What's next?**
  - Increase access capability to the subsurface of Mars with lightweight, low-power systems that can provide high science-value samples.
  - 20 m drill on a lander? 3 m drill on a rover?

Challenges to Drilling on Mars

- **Spacecraft Constraints**
  - **Low power and mass**
  - **Limited platform stiffness and reaction forces**
  - Stowed volume
- **Environmental Conditions**
  - Mars surface ambient pressure and temperature
  - Mars subsurface materials
    - hard rock
    - regolith imbedded with rocks
    - icy regolith and rock mixtures
  - **Minimal contamination (dry drilling)**
- **Getting to depth in poorly characterized material**
  - Comminution (breaking the rock)
  - Cuttings/debris removal from the borehole
- **Autonomy - what level is necessary?**

Subsurface Access Goals

- **The primary goal of the Mars Technology Program's Subsurface Access Base Technology Area is to develop sampling system technologies to satisfy future mission concepts**
- **To address varied mission needs, an NRA was released in 2003 that specifically requested automated systems that could sample**
  - to 0.5 m in regolith
  - > 1 m in rock and regolith
  - 10-20 m in rock and regolith
- **Missions of interest**
  - Scouts
  - Astrobiology Field Laboratory
  - Deep Drill Mission

Selected Tasks

- **Five tasks selected**
  - 3 single-segment, shallow samplers
  - 2 multi-segment deeper drills
- **MTP Performance Goals - based on potential future missions**

Depth	Power (W)	Mass (kg)	Stowed Volume (cm)	WOB (weight on bit)
Shallow (< 1 m)	30	4	50 x 25 x 25	<80 N
Deep (< 20 m)	80	40	100 x 100 x 100	<800 N

Some Autonomy Definitions

For drilling, sampling acquisition & delivery:

Category	Fault Response				Description / Notes
	Detection	Diagnosis	Prognosis	Remediation	
A0	Identify off-nominal condition(s)	Evaluate state of system	None	None	**Automated** Open loop control for drilling, sample acquisition and delivery
A1	Identify off-nominal condition(s)	Evaluate type of drilling fault	None	Abort drilling operations and put system in "safe" standby	**Semi-autonomous** Some closed loop control: closed-loop drilling control with respect to drill rate and platform reaction forces
A2	Identify off-nominal condition(s)	Evaluate type of drilling or sampling fault	None	Abort drilling and sampling operations and put system in "safe" standby	**Semi-autonomous** Primarily closed loop control: closed-loop drilling, sample acquisition and delivery
A3	Identify off-nominal condition(s)	Evaluate type of fault	None	Recover from fault and continue drilling/sampling operations	**Autonomous** Primarily closed loop control; failure diagnosis and recovery for drilling and sampling
A4	Identify off-nominal condition(s)	Evaluate type of fault	Predict future off-nominal condiditons	Recover from fault and continue drilling/sampling operations. Prevent future fault using preemptive actions	**Fully autonomous** Closed loop control; failure diagnosis, failure recovery/avoidance, and performance optimization for drilling and sampling

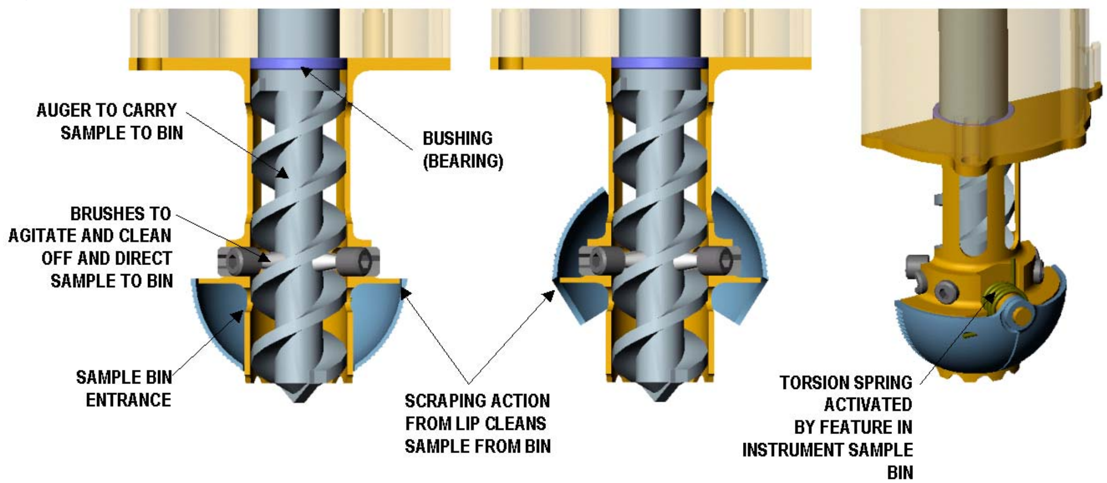
Fewer ground contacts

“MER-like” Rock Abrasion Tool autonomy

Low Force Sample Acquisition System (LSAS)

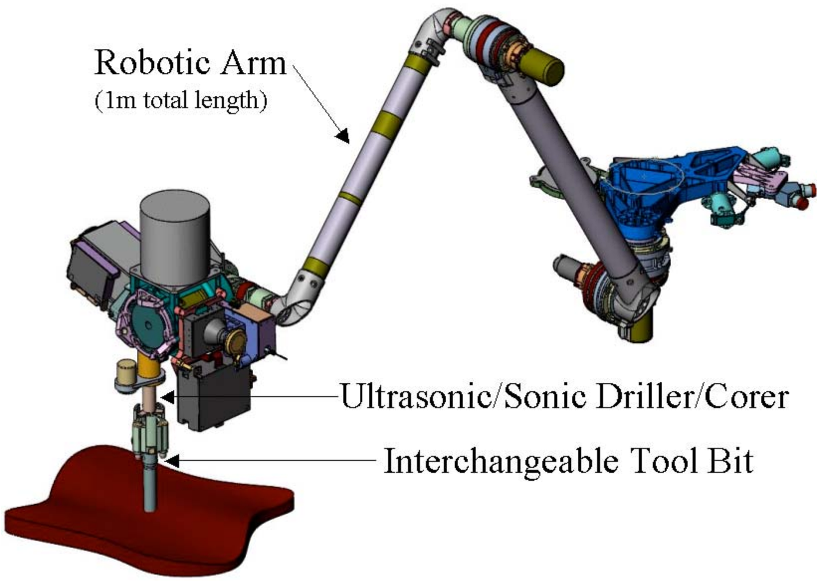
- **PI: Scott Stanley, Alliance Spacesystems, Inc**
- **Objective:** Collect 1.5 cm^3 powdered rock sample from the near surface (2 cm depth)
- **Features/Accomplishments**
  - Rotary percussive, single-segment drill
  - Low force drilling
  - Low mass, single-actuator system
- **Prototype currently under relevant environment testing at JPL**

LSAS prototype unit

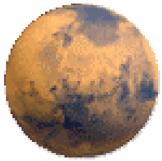


Mars Integrated Drilling and Sampling (MIDAS)

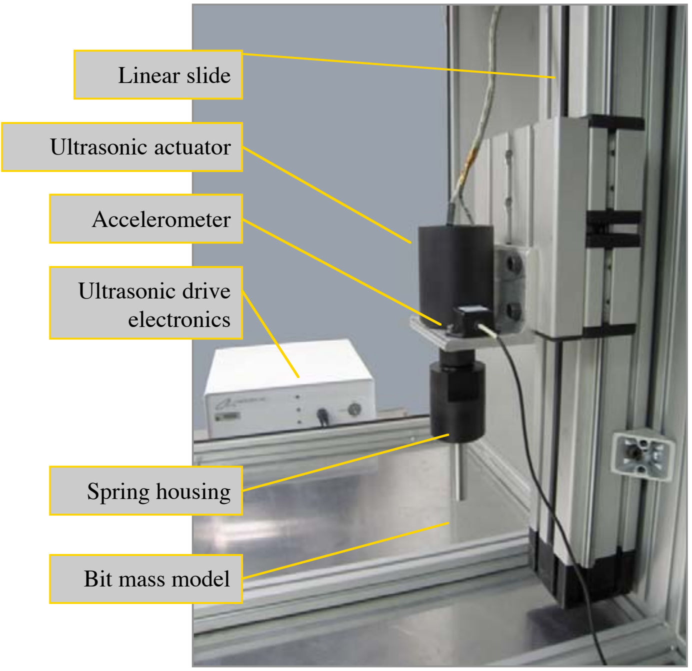
- **PI: Scott Stanley, Alliance Spacesystems, Inc**
- **Objective:** Collect unconsolidated regolith cores (1 cm diameter) from up to 0.5m depths
- **Features/Accomplishments**
  - Rotary percussive, single-segment drill
  - Arm-mounted, using MER robotic arm spare hardware
  - Interchangeable bit capability
- **Prototype unit ready for relevant environment testing October 2006**



Ultrasonic Sampler for Mars



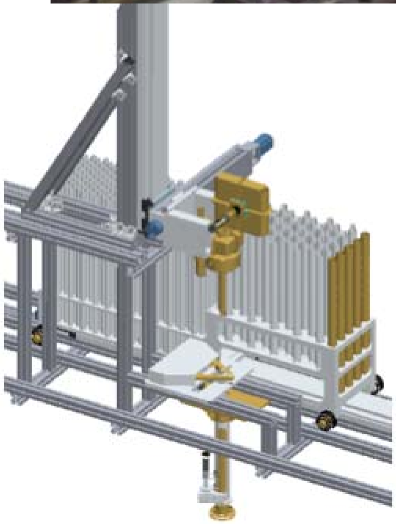
- **PI: Paul Bartlett, Honeybee Robotics**
- **Objective:** Collect 0.5 cm^3 of unconsolidated material from various depths up to 0.5 m below the surface
- **Features/Accomplishments**
  - Rotary percussive, single-segment drill
  - Low force (<20 N) comminution of hard rock achieved with ultrasonic actuator
  - Development of closed loop penetration algorithm to increase drilling efficiency
- **Prototype unit ready for relevant environment testing December 2006**



Breadboard unit for algorithm development

Modular Planetary Drill System (MPDS)

- **PI: Jose Guerrero, Swales Aerospace**
- **Objective:** Drill to 20 m and collect cores (1.5 cm diameter) and cuttings from hard rock and unconsolidated mixtures of rock, regolith and ice.
- **Features/Accomplishments**
  - Rotary, multi-segmented drill
  - Low power drilling is achieved in hard rock by removing cores and cuttings via wireline without removal of drill segments from the borehole
- **Test unit completing hard basalt field test**



Drilling Automation for Mars Exploration (DAME)

- **PI: Brian Glass, NASA-Ames**
- **Objective:** Develop automation to identify and recover from drill failures in augering drills
- **Features/Accomplishments**
  - Rotary, multi-segmented drill
  - Drilled 2.2 m into permafrost and breccia in two field seasons at Haughton Crater with < 200 W, demonstrating 8 drill faults during 50 hours of operation
- **Final field season, 2006**

DAME Drill testing in the Arctic

Benchmark Testing

- Performance can be highly dependent on specific test parameters such as platform compliance and target material properties
- A shallow testbed is being developed at JPL to evaluate < 2 m sampling systems on a common platform in Mars analog materials
- We plan to begin blind tests for each of the shallow sampling tasks by the end of FY07
- Benchmark testing of this kind will allow mission planners, technologists and the science community to compare the performance and evaluate the applicability of particular sampling systems to future missions

Field Testing

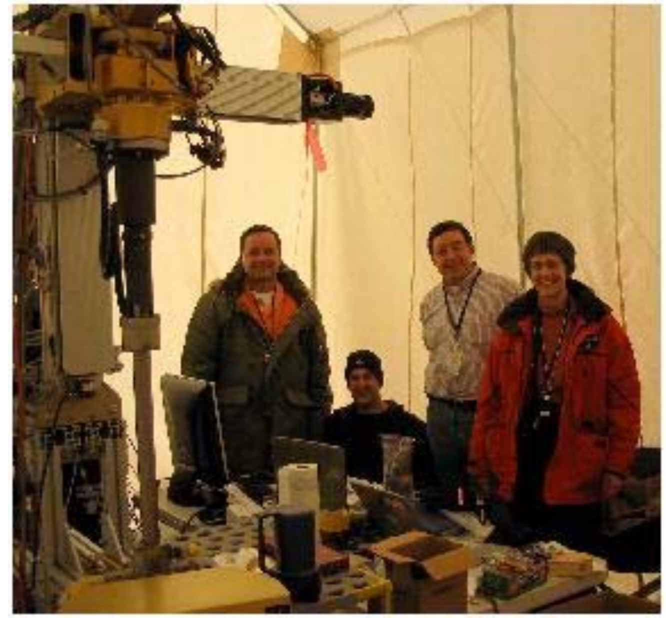
- **Evaluating the performance of deeper (>3 m) systems is more difficult as relying on lab testing alone becomes impractical (and expensive)**
- **A series of field tests has been recommended for the near-term development of 10-20 m class of drills:**
  - Homogeneous Sandstone - Gila Bend, AZ
    - Test conducted Dec 2002
  - Hard basalt (homogeneous) - Idaho Falls, ID
    - Feb/Mar 2006 - Test completed today!
  - Icy rock/regolith mixtures (permafrost)
    - Proposed for Alaska, Spring 2007
  - Heterogeneous mixture (dry) - TBD

Basalt Field Test

- **Justification**
  - To demonstrate a more flight-like drill (than Sandstone Field Test in 2002) at full depth (20 m) in material at the high end of the compressive strength range expected on Mars. Provides valuable "shakeout" of overall system.
  - Need to demonstrate semi-autonomous (A1) drilling
- **Duration**
  - Two weeks: February 21 - March 6, 2006
- **Subsurface environment**
  - Material: Columbia River Basalt
  - Location: Idaho National Lab (INL); Idaho Falls, ID
- **Borehole**
  - One 20-meter hole (minimum)
- **Power**
  - Demonstrate drilling & sampling at flight-like (<100 W) power levels

Basalt Field Test - Swales Team

- **Swales Aerospace (under 2003 NRA award)**
  - Multi-segmented, coring drill
  - Reached depth of 2.1 m total, ~1.7 m in basalt
  - Demonstrated low power drilling (<90 W for cutting basalt)
  - Successfully tested new bit design & magnetic joint design



Swales' MPDS in test tent

Recovered cores and cuttings

Basalt Field Test - Raytheon-UTD Team

Ratheon UTD (just after completion of SBIR Phase 2)

- **Tethered drill (Automated Drill Corer, ATC)**
- **Easy setup; started drilling quickly**
- **Reached maximum, depth of 78 cm; ~ 3 cm in basalt, using 60 W**
- **Became stuck on Day 7, while augering packed, wet cuttings**

The field testing of the ATC highlighted the importance of:

- **Optimizing the auger design to prevent clogging when conveying cuttings that a prone to caking.**
- **Incorporating a second anchor module to provide crawler-like locomotion for off-vertical boreholes**
- **Incorporating a back-reaming capabilities**
- **Developing a near-surface casing to stabilize the borehole entry**

Tethered Drill, Raytheon-UTD

Development Paths

- **Different development paths exist for each depth of drilling/sampling**
  - Shallow (1-3 m)
  - Deep (5-50 m)
  - Deeper (>50 m)
- **Actual schedule and cost of development is highly dependent on specific performance goals and validation techniques**
- **Combinations of analytical modeling, laboratory testing and field testing will likely be necessary to validate all of these samlpling systems**